WHEN HEALING HURTS

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ABSTRACT

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Over 100,000 lives are lost each year to Hospital Acquired Infections (HAIs). This is equivalent to five-hundred airplanes crashing at a rate of 1.36 per day. Adding insult to injury, 9.8 billion dollars are spent each year on Hospital Acquired Infections (HAIS). This staggering cost is composed of reactive CMS readmission penalties, reimbursements and lawsuits. It seems as though the reality of healthcare is - healing hurts.

Healthcare lacks a structured and scalable method for tackling HAIs - an increasing challenge due to an aging population and the rise of antibiotic-resistant organisms. The silos within healthcare, the complexity of prevention and the varied jurisdiction of healthcare professionals further escalate the severity of this problem. Simply put, handwashing, terminal cleans and aseptic techniques do not effectively protect patients. However, new methods for environmental optimization provide a new tool-kit as providers, administrators and physicians battle HAIs.

Cross industry techniques such as particulate tracking, laminar flow and bio-load identification can preemptively combat the most costly HAIs - surgical site infections (SSIs). This thesis will explore a comprehensive and hypothesis-driven approach to reducing SSIs through the environmental evaluation and modification of the Operating Room. The following work will construct the foundation for a scalable tool that will quantify, evaluate and eliminate Hospital Acquired Infections.

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Chapter 1. Understanding Hospital Acquired Infections

1.1 What are Hospital Acquired Infections?

Hospital Acquired Infections are iatrogenic - meaning they occur while patients are receiving care for another health-related condition. HAIs can happen in any health care facility, including hospitals, ambulatory surgical centers, end-stage renal disease facilities, and long-term care facilities. In the United States, the Center for Disease Control (CDC) estimates that of all HAIs:

32% are *Catheter-Associated Urinary Tract Infections (CAUTI)*
22% are *Surgical Site Infections (SSI)*
15% are *Pneumonia (Ventilator/Lung Infections)*
14% are *Central-line Associated Bloodstream Infections (CLABSI)*

Of these, Surgical Site Infections (SSIs) are a substantial cause of morbidity and prolonged hospitalization. SSIs are associated with a mortality rate of 3%. In addition, 75% of SSI - associated deaths are directly attributable to the infection itself, rather than external stressors.[1] These factors make Surgical Site Infections the most costly Hospital Acquired Infection type with an estimated annual $3.3 billion loss, and nearly 1 million additional inpatient-days annually.

Individual cost varies with the degree of infection, site of surgery and necessary materials. On average, a single SSI costs $25,000. This estimate increases to $90,000 when a prosthetic implant is involved.[2] But these costs may substantially increase due to liability and lawsuit awards. Although there are limits on liability payments in the state of Texas, there are no such limits in other states, such as Florida. In addition, these estimates do not factor physical

[1] Center for Disease Control: *Surgical Site Infection Event, Procedure Associated Module*
[2] Eloquest Healthcare, *Financial Impact of Surgical Site Infections*

therapy, emotional distress or additional treatments. Perhaps most costly is the impact on patient livelihood - as the patient is prevented from regaining normalcy.

Currently three types of Surgical Site Infections are recognized by the National Healthcare Safety Network (NHSN) Safety Component Manual:

> ***Superficial incisional:*** *involves skin and subcutaneous tissue of the incision.*
> ***Deep incisional:*** *involves deep soft tissues of the incision (e.g., fascial and muscle layers).* ***Organ/Space:*** *involves any part deeper than the fascial/muscle layers*

Hospital Acquired Infections will continue to rise due to demographic shifts, increased operations, chronic disease and antibiotic resistance. A swelling senior citizen population will create greater patient volumes, increasing HAI risk. US Seniors account for the majority of healthcare spending, and this number is projected to increase. By 2035, there will be 78.0 million people 65 years and older. But HAIs are not just a challenge for aging populations - the steadily increasing number of Pediatric Hospitals will also necessitate a change in strategy. Pediatric Hospitals will face similar vulnerabilities to infection. To further exacerbate the situation, Mercer estimates that by 2025, US providers will face a collective shortage of about 500,000 home health aides, 100,000 nursing assistants, and 29,000 nurse practitioners.[3]

The American Association of Orthopedic Surgeons (AAOS) lead author Matthew Sloan, estimates that by 2030, hip replacements are expected to number 635,000 (a 171 percent increase). Knee replacements could reach 1.28 million (a 189 percent increase). In 2060, hip replacements are projected to reach 1.23 million (330 percent increase) and knee replacements 2.60 million (382 percent increase).[4] Upsurges in operating room usage will further increase bio-load within the space. There is no doubt that these populations will also see a rise in surgical site

[3] Mercer's US Healthcare External Labor Market Analysis
[4] Sloan et al. *"Projected volume of primary and revision total joint replacement in the U.S. 2030 to 2060"*

infections if improvements are not enacted within the operating room. Infections will add to the financial burden as an entirely new prosthetic must be installed.

Chronic disease will further complicate the care continuum. Currently, 133 million Americans – 45% of the population – have at least one chronic disease. Chronic diseases are responsible for seven out of every 10 deaths in the U.S., killing more than 1.7 million Americans every year. Chronic disease complicates surgical procedures. Many chronic diseases are responsible for weakening the immune system of patients, making them more susceptible to infections during and after operations. In addition, chronic diseases are responsible for multiple re-hospitalizations, increasing patient risk of infection with each subsequent visit. In a retrospective comparison of 191 patients with surgical site infection and 378 uninfected controls by Kaye KS, the chronic disease score and ASA score were highly correlated.[5] The study demonstrated that examining chronic disease and the ASA score in concert increased the efficacy of the NNIS risk index. Thus, it is clear that chronic disease is an integral component of understanding current health, predicting for future health and adjusting for stressors.

Between 38.7% and 50.9% of microorganisms causing Surgical Site Infections are resistant to standard prophylactic antibiotics in the U.S. Antibiotic resistance is defined as the ability of microorganisms to resist the effects of drugs. Resistance to a specific antibiotic is based on the particular microorganisms previous exposure and developed defense mechanisms. In the U.S. alone, antibiotic resistant bacteria cause at least 2 million infections and 23,000 deaths a year resulting in a $55–70 billion per year economic impact. In particular, MSRA, Methicillin Resistant Staphylococcus Aureus is widespread in hospitals across the world. Antibiotic resistance compromises the safety and efficacy of implantation and transplantation for

[5] Kaye, K S et al. "Preoperative drug dispensing as predictor of surgical site infection."

orthopedics, which require the protection of antibiotics. Escalating severity of antibiotic resistance increases surgical suite risk thus increasing surgical site infections.

Identifying and assessing Hospital Acquired Infections is a complex task. An increasing elderly population, the upsurge of pediatric hospitals, rise of chronic disease and the threat of antibiotic resistance underscore the need for proactive prevention. Understanding the broader impact of HAI's on the healthcare system will allow identification of the levers necessary to fight pathogens.

1.2 Identifying Medical Errors

The Institute of Medicine's *To Err Is Human (1999)* called for a nationwide public mandatory reporting system to identify and learn from medical errors and other adverse events. The landmark work led to the creation of the National Healthcare Safety Network. For the first time in history, state organizations and forums began to report and quantify medical errors. Spurred by subsequent reports, The Deficit Reduction Act of 2005 required the Secretary of Health and Human Services to identify high cost and high volume preventable conditions that resulted in higher payments. Further research found that over $9.8 Billion was lost due to these medical errors. In an attempt to reform the healthcare system, the US Centers for Medicare and Medicaid Services (CMS) imposed regulations that denied payment for claims in which selected conditions were not present on admission (POA). After 2008, these regulations modified payment for acute care hospitalizations of Medicare fee-for-service beneficiaries if a medical condition could have been prevented.

Further defining claim compensation, the US Centers for Medicare and Medicaid Services (CMS) identified 10 Hospital Acquired Conditions (HACs) as being preventable under accepted guidelines. This practice helped standardized infection classifications within the

hospital environment - creating a common enemy among physicians and administrators. However, due to State discretion and the varying degrees of implementation, standardized data was and still remains elusive. States determine how collected data is analyzed, setting the individual parameters and standards for defining "good care".

1.3 The Affordable Care Act

Attempting to eliminate state variability, The Affordable Care Act created three distinct hospital pay-for-performance programs:

Hospital Readmission Reduction Program
Hospital Value-Based Purchasing
Hospital-Acquired Condition Reduction Program

The Hospital Readmission Reduction Program (HRRP) is a Medicare value-based purchasing program that reduces payments to hospitals with excess readmissions. The following six condition/procedure-specific 30-day risk-standardized unplanned readmission measures are accounted for:

Acute Myocardial Infarction (AMI)
Chronic Obstructive Pulmonary Disease (COPD)
Heart Failure (HF)
Pneumonia
Coronary Artery Bypass Graft (CABG) Surgery
Elective Primary Total Hip Arthroplasty and/or Total Knee Arthroplasty (THA/TKA)

The Hospital Value-Based Purchasing (VBP) Program is part of CMS' ongoing work to structure Medicare's payment system to incentivize providers for the quality of care they provide. This program adjusts payments to hospitals under the Inpatient Prospective Payment System (IPPS), based on the quality of care they deliver. Hospital performance on quality and cost measures is linked to the IPPS. The IPPS makes up the largest share of Medicare spending, affecting payment for inpatient stays in approximately 3,000 hospitals across the country.

Hospital VBP rewards acute care hospitals with incentive payments based on the quality of care, rather than just the quantity of services they provide.

The Hospital VBP Program is funded by reducing participating hospitals' FY 2020 base operating Medicare severity diagnosis-related group (MS-DRG) payments by an estimated 2%. The sum total amount of those reductions is then redistributed to hospitals based on their Total Performance Scores (TPS) that they earn for the year based on their performance on quality and resource use measures. What hospitals earn depends on the range and distribution of all eligible or participating hospitals' TPS scores for a Fiscal Year. It's possible for a hospital to earn back a value-based incentive payment percentage that is less than, equal to, or more than the applicable reduction for that Fiscal Year.

The Hospital-Acquired Condition (HAC) Reduction Program requires the Secretary of Health and Human Services (HHS) to adjust payments to hospitals that rank in the worst-performing 25 percent of all subsection (d) hospitals with respect to HAC quality measures. Hospitals with a Total HAC Score greater than the 75th percentile of all Total HAC Scores (i.e., the worst-performing quartile) are subject to a 1 percent payment reduction.

1.4 The Financial Disconnect

The Hospital Readmission Reduction Program, Hospital Value-Based Purchasing Program and the Hospital-Acquired Condition Reduction Program fail to fix the root problem - fighting infection at the source. Rather than equipping hospitals nation-wide with effective resources for prevention or stimulating innovations, these programs cause hospitals to individually scramble to develop new methods for prevention and tighten aseptic practices to avoid losing Medicaid revenue. Efforts would be better spent withholding capital for innovations within the operating suite, the delivery room and patient recovery spaces. According to the U.S.

Census Bureau and the Centers for Medicare and Medicaid Services, total national health expenditures are expected to reach $4 billion by 2020 and $5 billion by 2025.

Over 800 hospitals will lose Medicaid funding this year due to high infection rates and patient injuries. This is the highest number of hospitals that have lost their incentives since the federal government launched the Hospital Acquired Conditions (HAC) Reduction Program. According to a Kaiser Health News Analysis, 1,756 hospitals in the United States have lost Medicaid reimbursements at least once. More frightening, 110 hospitals have remained in this category the fifth straight time. Even if their rates do improve from the previous year - the quarter of general hospitals with the highest rates lose funding.

Some hospitals protest these practices, arguing that the program's design creates an arbitrary cutoff. The American Hospital Association calculated that only about 41 percent of the 768 hospitals penalized in 2017 had HAC scores that were statistically significantly higher than hospitals not being penalized. According to Nancy Foster, the Association's Vice President for Quality and Patient Safety, "there are not statistical differences that would warrant a quarter of the hospitals in America getting a penalty."[6] However, hospitals have a moral and ethical duty to their patients. Statistical differences aside, having even ONE Hospital Acquired Infection is unacceptable. Healing should not produce greater harm.

It is important to note that these incentive based programs have inspired hospitals to test new processes. For example, Seton Family Hospitals set a new standard while investigating birth trauma rates. Leveraging analytics, Seton pioneered a system wide effort to achieve zero preventable injuries and deaths by July 2008. Installing a new protocol of reducing elective inductions prior to 39 weeks, Seton Family Hospitals were able to essentially reduce the birth

[6] Rau, Jordan.*"Medicare Trims Payments To 800 Hospitals, Citing Patient Safety Incidents"*

trauma rate to zero. Recognizing this critical innovation to policy, The Joint Commission presented Seton with the Ernest Amory Codman Award. Now, hospitals across the United States follow a similar policy - further preserving the health of mothers and their newborns.

However, the broad inability to reduce Hospital Acquired Infections through incentive programs suggests a disconnect between healthcare systems and quality improvement outcomes. Although the loss of revenue draws the attention of administrators and boards, the statistics presented demonstrate that the loss of funding is not effectively impacting necessary change processes. Patients still come into contact with pathogens. In order to understand why the Hospital Readmission Reduction Program, Hospital Value-Based Purchasing Program and the Hospital-Acquired Condition Reduction Program fail to create change, one must examine administrative and departmental structure.

In the attempt to fight medical errors, administrators must play a massive "game of telephone" in order to investigate. CEOs and COOs reach out to Quality Directors, clinical leaders, surgeons and their teams, but with so many moving components it is often difficult to determine where, how or why an infection occurred. At times, these teams may look to EVS and plant operators for further explanations into how the environment may have impacted a certain occurrence. Smart leaders look for trends in data, hoping to gain perspective. But the system lacks a concrete set of operations - in fact it cannot be called a system at all. It is a retroactive set of questions. At the end of the investigation, it is unlikely that the "game of telephone" has produced a proactive solution. Innovative leaders might push new program initiatives to assist with increasing handwashing rates or affirm a specific aseptic technique. However, the problem remains - current techniques are not able to proactively account for the vast array of pathogens, while factoring the complexity of the human condition and determining the state of the hospital

environment. Leaders may be able to target one or two significant variables but the current mental model lacks the scalability to protect patients.

Ultimately, the current incentive system does not equip hospitals with the necessary tools to eliminate pathogenic exposure. Solving surgical site infections requires a procedure-based methodology. With over 100,000 deaths and 9.8 - 38 billion dollars lost in revenue each year, proactive protocols must be installed. It is no longer acceptable for healing to be harmful.

1.5 Data That Tells a Story

A successful HAI surveillance program includes the use of epidemiologically-sound definitions, consistent monitoring, rate stratification, associated risk factors, individual patient health and data feedback. Each of these components creates a narrative for data comprehension by healthcare practitioners and ambulatory workers. Quality Management Boards and Infection Prevention staff play a critical role in gathering, interpreting and distributing this data.

Collaboration between Physicians, Quality and Infection prevention is no easy feat due to the vastly different domains and stakeholders. Without clear deliverables and an empathetic approach, the investigation process of a surgical site infection may be perceived as a search for blame. Physicians and quality management must work closely to gain unbiased evaluations and cultivate best practices. Empathy is critical to this taxing process as these teams evaluate a number of variables in order to determine the root cause. Some variables within the operating room include the adherence to prophylactic antibiotic guidelines, the aseptic pre-operative practices, the follow-up of surgical wounds after hospital discharge, the oxygenation status of the patient and the patient's body temperature.

In particular, Quality faces significant barriers in collecting effective data. Collecting the numbers of surgical site infections rates appears simple, but it is not. Due to separation of units

and practices, surgical site infection rates are often housed under different surgical departments, administrators and teams. In addition, determining significant data requires complex investigation. In some cases, data will clearly identify a specific surgical team with a high infection rate that is linked to a specific aseptic practice or lack thereof. But in most cases, surgical site infections are seemingly unattributable. Complications surrounding the patient's general health and physical environment play an almost untraceable role because hospitals lack a means to quantify pathogenic bio-load.

Infection Prevention staff give crucial insight to understanding the bacteria or virus involved in the SSI. By understanding the vector of infections and the organism, Infection Prevention staff can better equip physicians with the tools to fight infections. Infection Prevention can also equip the Environmental Services within a hospital with the tools and knowledge to perform effective terminal cleans. Based on the biological load seen in patients, Infection Prevention can help tailor cleaning solutions for better patients outcomes. However, this is still a reactive process, pathogens need to be identified and dealt with before patients are exposed.

1.6 Tracking SIR within a Hospital

The Centers for Disease Control and Prevention's National Healthcare Safety Network (NHSN) uses surgical site infection data to create an outcome based measurement called the Standardized Infection Ratio (SIR). According to the NHSN, the standardized infection ratio (SIR) is a summary measure used to track HAIs at a national, state, or local level over time. By understanding and modifying SIR, hospitals will be able to better inform their patients and practitioners of their risk for infection.

The SIR adjusts for various facility and/or patient-level factors that contribute to HAI risk within each facility. The method of calculating an SIR is similar to the method used to calculate the Standardized Mortality Ratio (SMR), a summary statistic widely used in public health to analyze mortality data. In HAI data analysis, the SIR compares the actual number of HAIs reported to the number that would be predicted, given the standard population (i.e., NHSN baseline), adjusting for several risk factors that have been found to be significantly associated with differences in infection incidence. Currently, SIRs are calculated for the following HAI types:

Central Line-Associated Bloodstream Infections (CLABSI)
Mucosal Barrier Injury laboratory-confirmed bloodstream infections (MBI-LCBI)
Catheter-Associated Urinary Tract Infections (CAUTI)
Surgical Site Infections (SSI)
***Clostridium difficile* infections (CDI)**
Methicillin-Resistant *Staphylococcus Aureus* bloodstream infections (MRSA)
Ventilator-Associated Events (VAE).

An SIR greater than 1.0 means that HAIs in a facility or state than were predicted, and the facility is classified as "Worse than the National Benchmark". If the SIR is less than 1, then the facility had fewer HAIs than were predicted and is classified as "Better than the National Benchmark". If the confidence interval includes the value of 1, then there is no statistical difference between the actual number of HAIs and the number predicted, the facility is classified as "No Different than National Benchmark". If the number of predicted infections is less than 1, the SIR and confidence interval cannot be calculated.

The SIR is calculated by dividing the number of observed infections by the number of predicted infections. The number of predicted infections is calculated using multivariable regression models generated from nationally aggregated data during a baseline time period. It is important to note that the SIR is not a pooled mean rate. This is purposeful - a pooled mean rate cannot account for differences in risk between populations. Pooled mean rates lose comparability

over time and across entities. For example, calculating rates from two facilities serving entirely different patient populations can lead to an unfair comparison.

NHSN uses either a logistic regression model or a negative binomial regression model to perform the calculation. A logistic regression model of the risk factors found to be significant for abdominal hysterectomy is shown to the right. The table shows each risk factor's contribution to the SIR varies, as represented by the parameter estimate for each factor. Parameter estimates describe the relationship between the variable and the risk of SSI; positive parameter estimates indicate that the risk of SSI increases with increasing values of the variable. Negative parameter estimates indicate that the risk of SSI decreases with increasing values of the variable.

Table 1. Risk Factors for SSI HYST: Complex 30-Day Model (2015 Baseline)

Factor	Parameter Estimate	P-value	Variable Coding
Intercept	*-5.1801*	-	-
Diabetes	0.3247	<0.0001	**Yes**= 1 **No**= 0
ASA Score	0.4414	<0.0001	**1**= 1 **2**= 2 **3**= 3 **4/5**= 4
Body Mass Index (BMI)	0.1106	0.0090	**≥ 30**= 1 **< 30**= 0
Patient Age	-0.1501	<0.0001	**Patient's age/10**
Oncology Hospital	0.5474	0.0005	**Oncology hospital**= 1 **Non-oncology hospital**= 0

According to the CDC, using the SIR, one could evaluate the risk of infection to a given patient. Using the regression model, it can be determined that a 32 year old woman with diabetes, a BMI score of 29, an ASA score of 2 and operated on in an oncology hospital would have a 2% risk. As demonstrated, the SIRs can be risk-adjusted by taking into account factors, such as type of patient care location, bed size of the hospital, patient age, and other variants.

$$logit\,(\hat{p}) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_i X_i \text{ , where:}$$

α = Intercept

β_i = Parameter Estimate

X_i = Value of Risk Factor (Categorical variables= 1 if present, 0 if not present. Refer to "Variable Coding" column in Table 1 above.)

i = Number of Predictors

But what does this really tell providers? And, is this reliable? This percentage can only be validated by checking against the p-value. In order to ensure that the most reliable and precise calculation is excised, the SIR must continually be refined. Although the calculation accounts for the hospital's history and a few important patient variables, it remains a mass generalization. Other scientists recognize this need and are working to build better, more specific models towards this end. For example, a predictive model for surgical site infection risk after surgery for high-energy lower-extremity fractures: "Development of the risk of Infection in Orthopedic Trauma Surgery Score" is currently under review. This is just one of many examples of surgical specification for patient benefit. But even these models miss an important piece of the puzzle. A comprehensive risk adjustment needs to include the Operating Room environment and associated surgical team. By examining the biological load of each individual operating room directly, the patient receives a comprehensive analysis of their future care based upon relevant, current variables.

Ultimately, the SIR must be customized even further in order to improve patient comprehension and future prevention. Telling a patient they have a 2% risk of receiving an infection does not provide a tangible understanding of what may happen over the course of a procedure or during post-operative recovery. Delivering comprehensive and compassionate healthcare necessitates informed patients. In addition, greater depth and clarity shed upon surgical site infections, will allow for real - time development of solutions through better variable manipulation.

Again, I challenge you to compare the models of other industries. In banking and insurance, risk calculations are highly comprehensive in order to assess loans. In addition, this

calculation can be adjusted for extraneous factors. The same thought process should be applied to healthcare.

Chapter 2: Know Thy Enemy

Sun Tzu wrote in The Art of War, "If you know the enemy and know yourself, you never need to fear the result of a hundred battles. If you know yourself but not the enemy, for every victory gained you will also suffer a defeat. If you know neither the enemy nor yourself, you will succumb in every battle."

Healthcare wages a constant battle against pathogens. Pathogens shed by patients and staff contaminate surfaces for days and pose a threat to their safety. Environmental screening confirms repeated contamination of items, equipment, and general sites in bed spaces and rooms of colonized or infected patients and often throughout multiple clinical areas in a health care institution[7]. Health care workers' hands touch these contaminated surfaces during patient care, which increases the risk of onward transmission to others.

Increasing the complexity of prevention - infection rates and bacteria vary per hospital. The rituals, practices and culture instilled by each cohort of administrators, departments physicians and nurses create a unique ecosystem. Thus within a single hospital, department and even floor, biological load varies. For example, ICU patient rooms do not have the same pathogenic bio-load as operating rooms or the ER. The pathogens that move within these spaces are different. Therefore, differentiated environmental management is critical to patient outcomes. In order to ascertain proper management and elimination methods, it is critical to understand pathogens and their characteristics intimately. However, for the sake of brevity, this section will examine the pathogens most common to surgical site infections.

[7] Bhalla A, Pultz NJ, Gries DM, Ray AJ, Eckstein EC, Aron DC, Donskey CJ. 2004. *Acquisition of nosocomial pathogens on hands after contact with environmental surfaces near hospitalised patients.*

2.1 Prevalent Pathogens

The most prevalent antibiotic resistant microorganisms are mnemonically referenced as ESKAPE[8]. Each of these microorganisms have caused significant patient morbidity and mortality in hospitals across the United States. In order to effectively combat them, it is necessary to characterize their components and mechanisms. Characterization recognizes the unique structure of each pathogen and helps build effective methods of prevention. ESKAPE consists of:

Enterococcus Faecium
Staphylococcus aureus
Klebsiella Pneumoniae
Acinetobacter Baumannii
Pseudomonas Aeruginosa
Enterobacteria

Enterococcus faecium is a facultative anaerobic Gram-positive bacterium. A facultative anaerobe can survive with or without oxygen. If oxygen is present a Enterococcus Faecium will produce ATP by aerobic respiration. If oxygen is absent, it is capable of switching to fermentation. Enterococcus are smaller than 0.2 microns in size and naturally colonize the gastrointestinal tract of humans and animals. Intrinsic resistance to cephalosporins, aminoglycosides, lincosamides and streptogramins has created additional resistance to glycopeptides and β-lactam antibiotics, complicating the treatment of clinical infections. The most common and dangerous of these strains is Vancomycin Resistant Enterococcus, associated with a 2.5-fold increase in mortality. Enterococcus has been shown to persist for as long as 4 months on surfaces. It thrives best within high humidity settings around 80%. In a clinical

[8] Santajit, Sirijan, and Nitaya Indrawattana. "*Mechanisms of Antimicrobial Resistance in ESKAPE Pathogens.*"

setting, VRE was shown to persist through an average of 2.8 standard room cleanings[9], thereby acting as a continual source for possible transmission. This underscores the necessity of developing new methods for prevention. Many hospitals do not have the time or man-power to clean a patient room or operating facility three separate times due to bed turnover and admission rates.

Staphylococcus Aureus is a facultative anaerobic Gram-positive bacterium. S. Aureus typically lives in the noses and on the skin of humans and is 0.8 - 1.2 microns in diameter. The most prevalent types of S. Aureus infections within a healthcare facility occur due to:

Methicillin-Resistant *Staphylococcus aureus* (MRSA)

Methicillin-Susceptible *Staphylococcus aureus* (MSSA)

Vancomycin-Intermediate *Staphylococcus aureus* (VISA)

Vancomycin-Resistant *Staphylococcus aureus* (VRSA)

Resistant strains of S. Aureus persist on dry surfaces, hard surfaces for multiple months. On softer surfaces, resistant strains may only survive for a few weeks. In addition, S. Aureus is one of the few pathogens found to persist longer at low humidity than high humidity.

Klebsiella Pneumoniae is an aerobic, gram-negative, encapsulated, non-motile bacterium. Similar to the other pathogens discussed, it is found naturally in the environment. The bacterium typically colonizes human mucosal surfaces of the oropharynx and gastrointestinal (GI) tract and has been associated with pneumonia in the alcoholic and diabetic patient population. The bacterium survives within the immune system and gains antibiotic resistance due to a polysaccharide capsule which evades opsonophagocytosis and serum killing.[10] Klebsiella

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[9] Matthew L. Faron, Nathan A. Ledeboer, and Blake W. Buchan *"Resistance Mechanisms, Epidemiology, and Approaches to Screening for Vancomycin-Resistant Enterococcus in the Health Care Setting"*

[10] Paczosa, Michelle K, and Joan Mecsas. *"Klebsiella pneumoniae: Going on the Offense with a Strong Defense."*

Pneumoniae's ideal growth temperature ranges from 95° to 98.6 °F, 80-90% humidity and an ideal pH level of 7.2. The bacteria ranges from 0.3 to 1.0 μm in width to 0.6-6.0 μm in length.

Acinetobacter Baumannii is a Gram-negative bacillus. It is aerobic, pleomorphic and non-motile. Pleomorphism means a bacteria can alter its size and shape based on environmental conditions. *Acinetobacter* spp. are short, plump, typically 1.0–1.5 μm by 1.5–2.5 μm in size as measured during the rapid phase of their growth but often develop into more coccoid in the stationary phase, usually present in pairs or long chains of variable length[11]. *A. baumannii* has a high incidence among immunocompromised individuals, who have experienced a prolonged (> 90 d) hospital stay. It is an emergent concern among healthcare professionals due to increased prevalence of infected combat troops returning from conflict zones and increased incidence of multidrug-resistant (MDR) strains.[12] Similar to S. Aureus, Acinetobacter Baumanniishown colonizes the skin. It is also found in high numbers from the respiratory and oropharynx secretions of infected individuals. The bacillus grows fastest at high humidity.

Pseudomonas Aeruginosa is a gram-negative opportunistic pathogen that causes severe acute and chronic infections at different sites within the body such as urinary tract, skin (burn or surgical wounds), and the respiratory tract. It is a rod about 1-5 μm long and 0.5-1.0 μm wide. It is found widely in nature and can survive for months at a time on inanimate surfaces. The ideal growth temperature is between 77 °F to 98.60 °F. Its ability to grow at 107.60°F distinguishes it from many other *Pseudomonas* species.

Enterobacter is a motile facultative, anaerobic, gram-negative bacilli belonging to the family *Enterobacteriaceae.*[13] Similar to the other pathogens discussed, it is found naturally in the

[11] Saad B. Almasaudi, *"Acinetobacter spp. as nosocomial pathogens: Epidemiology and resistance features"*
[12] Howard, Aoife et al. *"Acinetobacter baumannii: an emerging opportunistic pathogen."*
[13] Octavia S., Lan R. (2014) The Family *Enterobacteriaceae*.

environment. Enterobacter species cause infections affecting the lungs, urinary tract, intra-abdominal cavity and intravascular devices. Optimum growth occurs at 86°F, but most clinical strains grow at 98.6°F. Generally, the bacilli are 0.6-1.0 um wide x 1.2-3.0 um long. VRE can last from 5 days to 5 months on dry surfaces.

Clostridium difficile is a gram-positive species of spore-forming bacteria. Clostridioides are anaerobic, motile bacteria, ubiquitous in nature, and especially prevalent in soil. It causes diarrhea and colitis (an inflammation of the colon). Clostridium difficile infections can last for up to five months on dry surfaces.[14] C. Diff is fairly large, ranging from 3 - 4 microns. Optimum growth occurs from 86°– 98.6°F, and the organism grows at 77°F and 113°F.

Ultimately, each pathogen within the healthcare space is unique and must be treated as such. This is not a comprehensive list, and needs to be continued if we hope to win this war. Methods of prevention must be differentiated in order to account for differences in surface, humidity preference and transmission methods. Pathogen removal and reduction requires a prescriptive approach. One size does not fit all. Families and children should not experience risk because hospitals and healthcare employees are not customizing their approach to the pathogenic ecosystem.

2.2 Customizing Tools for Reduction

Hospital administrators, Infection control and Environmental Services must customize their approach to reduction. As antibiotic resistance rises, multi-faceted and multi-step methods will be integral to prevention. Pathogenic management must begin before the patient steps through the hospital doors, throughout their stay and long after they have left. No longer can

[14] Claro, Tânia et al. "*Detecting Clostridium difficile spores from inanimate surfaces of the hospital environment: which method is best?.*"

"one-size fit all". Solutions must be tailored to meet each patient and environment's unique biological load. There is more than enough data to inform this process - the difficulty lies within consciously creating scalable actions and outcomes. Ultimately, comprehensive prevention will require a "puzzle-piece" approach - each tactic interlocking to create a continuum.

A key tactic to success is environmental management. Environmental sampling suggests that the bed frame, bedside table and locker; nurse call button, bed control and light switch are prime sites for pathogens such as methicillin-resistant *Staphylococcus aureus* (MRSA) and vancomycin resistant enterococci (VRE). Thus we will explore methods for prevention that directly impact these surfaces: antiseptics, disinfectants and photodynamic light therapy. Each of these will have significant weaknesses, but it is my belief that a combination of methods and materials will allow healthcare professionals to successfully combat antibiotic resistant pathogens and protect their patients.

For antiseptics and disinfectants, one of the greatest predictors of efficacy is compliance with necessary dwell time. In 2009, the Association for Healthcare Environment (AHE) published recommended guidelines for environmental cleaning in healthcare. AHE suggests effective patient room cleaning upon discharge should take about 40 to 45 minutes. However, due to influx in cases or emergency situations hospital administrators may push turnover times down to 15 - 20 minutes. This poses a serious problem for pathogenic removal.

The emergence of multidrug-resistant gram-negative bacteria creates a need for surface disinfectant cleaners (SDCs) that are effective against these bacteria for use in high risk areas around patients and on multi-touch surfaces. A study by Mirja Reichel determined that surface disinfectants containing alcohol and an amphoteric substances (AAS), oxygen-releasers (OR), and surface-active substances (SAS), or surface-active-substances plus aldehydes (SASA; two

formulations) can be used to effectively combat ESKAPE. It is important to note that this study tested dwelling times of 30 and 60 minutes - well between or above a hospital turn-over time.

However, literature reports on SAS efficacy are conflicting. Some studies found that SAS are not sufficiently effective against gram-negative bacteria or that efficacy is lower against gram-negative than against gram-positive bacteria. Other studies found that SAS are effective. Outbreaks of contaminated SAS disinfectant solutions have been reported. Some strains, particularly biofilm-forming species, survive or even multiply in SAS disinfectants at concentrations at which they are normally used and this can result in infections such as septicemia. Such conflicting results demonstrate the difference dwell time and pathogenic make-up have on efficacy.[15] If we hope to win the war against hospital acquired infections, we cannot pursue a singular method.

Another course of action to prevent the spread of multidrug-resistant *E. faecium* in health care settings is Chlorhexidine (CHX). CHX is a bisbiguanide agent able to reduce bacterial membrane fluidity or disrupt the structural integrity of the membrane, causing increased permeability and leakage of cell contents and, ultimately, cell death. In health care, CHX is often used in surgical scrubs for preoperative skin preparation, impregnated washcloths for postoperative wound care, daily patient bathing, and oral care of intubated patients. Regular bathing of patients with CHX significantly reduces the colonization by VRE and other multiresistant organisms in intensive care units and general medicine wards. Recently, increased tolerance to these compounds has been reported for Gram-positive cocci, and this could contribute to future co- or cross-selection for antibiotic resistance. In addition, subinhibitory

[15] Reichel, Mirja et al. "*Efficacy of surface disinfectant cleaners against emerging highly resistant gram-negative bacteria.*"

concentrations of CHX induce the expression of genes involved in vancomycin and daptomycin resistance in enterococci.[16]

Pathogenic management may also come in the form of light. According to a study by Duke Health[17], a UVC light, is helping to reduce transmission of antibiotic resistant organisms in patient rooms. Killing bacteria with UV light requires the use of germicidal wavelengths of 185-254 nanometers (nm). The UVC light collectively cuts Methicillin-resistant Staphylococcus aureus (MRSA), vancomycin-resistant enterococci (VRE), C. difficile and Acinetobacter by 30% in rooms in which patients must stay overnight. Trials further combined this method with quaternary ammonium followed by UV light, chlorine bleach instead of quaternary ammonium and no UV light, and cleaning with bleach and UV light. Results demonstrated that the most effective strategy against MRSA was using quaternary ammonium followed by UV light. However, the researchers also determined that using chlorine bleach instead of quaternary ammonium cut transmissions of VRE by more than half. Adding UV light to the bleach regimen was even more effective; it cut VRE transmission by 64 percent. Overall, this demonstrates the importance of mixed-media enhancements within the hospital environment.

It is important to note significant drawbacks to UVC light. The method poses a risk as conventional germicidal UV light is a human health hazard and can lead to skin cancer and cataracts, which prevents its use in public spaces. This means that the operation of the UVC light must occur from a distance. Duke has piloted a UVC robot that can control light exposure and timing. However, this process still creates an additional, time consuming step in the lengthy EVS

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[16] Guzmán Prieto, Ana M et al. *"The Two-Component System ChtRS Contributes to Chlorhexidine Tolerance in Enterococcus faecium."*

[17] Dr. Deverick J. Anderson et al. *"Enhanced terminal room disinfection and acquisition and infection caused by multidrug-resistant organisms and Clostridium difficile (the Benefits of Enhanced Terminal Room Disinfection study): a cluster-randomised, multicentre, crossover study"*

process. In order to minimize this risk, researchers have begun to experiment with Far UVC light. Far UVC Light "has a very limited range and cannot penetrate through the outer dead-cell layer of human skin or the tear layer in the eye, so it's not a human health hazard," Dr. Brenner, director of the Center for Radiological Research and professor at CUIMC noted. "But because viruses and bacteria are much smaller than human cells, far-UVC light can reach their DNA and kill them." [18]

In order to circumvent the dangers of UV waves, scientists have turned to studying variations of visible light and far UV waves. A pilot program at Maury Regional Medical Center in Colombia, Tennessee has implemented 405nm visible light in Operating Room lamps to combat pathogens. The waves excite naturally occurring porphyrins, producing an intracellular Reactive Oxygen Species. Similar to bleach, this process created an oxidative environment preventing the organism from repopulating the space. The blue light irradiation produced a statistically significant dose-dependent reduction in both the number and the aggregate area of colonies formed by each bacteria strain ($P<0.001$). The study concluded that maximum eradication of the US-300 (92.1%) and the IS-853 colonies (93.5%) was achieved within 9.2 and 8.4 minutes of exposure, respectively. Explore combinations further and failings. This new tactic confers significant advantages. Blue irradiation lights can be operated while surgical procedures occur in the operating room without posing a risk to patient or physician health. In addition, the lights may remain running during the terminal clean process, enabling greater time effective usage. Blue light irradiation can find applications in other areas of the hospital such as patient rooms and the pharmacy.

[18] John Wallace. *"UV Sterilization: Far-UVC light kills airborne flu viruses without danger to humans"*

We've explored several environment altering solutions - this is by no means an exhaustive list. It is critical to reinforce that one of these solutions alone will not win the war against antibiotic resistant pathogens. A combination of tactics and methods will be crucial to getting and keeping patients healthy.

2.3 Selective Cohabitation, Rehabilitation and Elimination

Ancient philosopher Aristotle postulated: "Nature abhors a vacuum." In many ways, this sentiment has withstood the test of time. Freeman Dyson, an American theoretical physicist and mathematician known for his work in quantum electrodynamics, solid-state physics, astronomy and nuclear engineering postulates a similar concept: " the universe is guided by a principle of maximum diversity."

Nature cultivates heterogeneity. The most tangible example sprouts from within groomed lawns and agricultural fields. All materials or and methods defied, a vast array of insects and plant encroach on these carefully pruned areas. However, 20 years ago, farmers and gardeners were given a new technology that seemed to defeat nature. These genetically engineered crops and plants could tolerate doses of the herbicide glyphosate - the chemical known as Roundup.[19] It could be sprayed right over crops, eliminating weeds. It was an incredible success - until it wasn't. Eventually, a strain of weed was discovered that Roundup, known as Palmer amaranth, or pigweed could not kill. Pigweed spread rampantly, wreaking havoc on the farming industry as biotech companies scrambled to deploy new genetically engineered crops and herbicides. There was some success in this process, but eventually each of these would fail.

[19] *As Weeds Outsmart The Latest Weedkillers, Farmers Are Running Out Of Easy Options*

In recent years, agriculture has stopped trying to win the war on homogeneity. Their tactic now, is to turn enemies into friends. Fields that were once dominated by a singular genetically engineered crop are now partnered and propagated with carefully selected organisms. These partner crops are nurtured for their ability to confer environmental advantages such as: deterring weeds, providing nutrients, warding away pests or attracting pollinators. Thus, the agricultural world has turned from total elimination and towards selective cohabitation with a fair amount of success. A similar tactic should be deployed in hospitals.

A relatively new hypothesis posits that hospital-acquired infections are being driven not by the existence of harmful microbes but by the absence of helpful species. Researchers propose that hospital microbiomes form a key part of a hospital's "immune system" and in some cases may help protect patients against infectious diseases. Capturing the hospital microbiome has created a significant roadblock due to the inability to grow 99% of bacteria in a culture. However, research into the human microbiome has demonstrated that antibiotics disrupt the normal array of microbes that live in and on our bodies. Jack Gilbert, an environmental microbiologist at Argonne National Laboratory, believes that this concept may be key to rethinking hospital sterility.[20] Thus, the question thus becomes, "What organisms do we choose to cohabitate hospitals?"

The answer requires a deeper understanding of elimination and rehabilitation. Although nature favors heterogeneity, it controls diversity through a hierarchy of organisms. The bacteriophage is one of these organic microbial population regulators. With an estimated 10^{31}-10^{32} phages in the world at any given time, they make up the most abundant biological entity on Earth and play a crucial role in regulating bacterial populations. In addition, phages are

[20] Kelley ST, Gilbert JA. *"Studying the microbiology of the indoor environment."*

responsible for the death of approximately 20%-40% of all marine surface bacteria every 24 hours. [21] But phages, do not just eliminate bacteria - they strengthen them. Phages are the oldest purveyors of horizontal gene transfer, enabling bacteria to adapt to their environment and new threats.

Injecting their DNA into the host bacterium, phages replicate and kill the host, thereby releasing a multitude of newly assembled phages. Phages are easy and cheap to culture in any microbiology laboratory and can be selected to target specific bacterial strains effectively. Previously, phages were passed over by researchers in favor of antibiotics due to their specificity constraints. Unlike antibiotics, a phage may only target one type of bacteria at a time. However, it is this specificity that makes them a powerful asset in the war on antibiotic resistant pathogens. As research progresses phages will be cultivated to target specific strains of MRSA or VRE with high success rates.

It is important to understand phage mechanisms. Phages have two life cycles: lytic and lysogenic. In the lytic life cycle, phages infect and rapidly kill their infected host cells. This outcome clearly fulfills the end goal - total destruction of MRSA or the pathogen of choice. Yet, there is debate as to whether this method of implementation will simply act as a short term solution. Similar to antibiotics, the bacteria is eliminated entirely. As phages proliferate hospital environments, the microbiome will shift with unexpected consequences. The fall of one organism will lead to the rise of a new threat or a new self-preserving defense mechanism. Thus, with time, neither of these outcomes achieve their initial goal, and the war on pathogens begins again.

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[21] Derek M Lin, Britt Koskella, and Henry C Lin, *"Phage therapy: An alternative to antibiotics in the age of multidrug resistance"*

One solution to this conundrum may lie in the lysogenic life cycle. In the lysogenic life cycle, phages integrate into their host genome, or exist as plasmids within their host cell. The lysogenic life cycle may alter the phenotype of the bacterium by expressing genes that are not expressed in the usual course of infection. This process is known as lysogenic conversion. Lysogenic conversion has been used organically by bacteria for centuries - developing prophages that enable horizontal gene transfer and help strengthen virulence factors. In fact, two-thirds of all gamma-proteobacteria and low-G+C gram-positive bacteria harbor prophages; these include *Escherichia coli* O157 Sakai and *Salmonella* spp. [22] However, in other cases, prophages integrate into protein-encoding genes and lysogenization is linked to the loss of a protein function (negative lysogenic conversion phenotype). Well-characterized cases are the lipase- and the β-toxin-negative phenotype due to the integration of prophage L54a and phi13, respectively, into the *S. aureus* genome. This demonstrates that prophage integration can disrupt or modulate bacterial gene expression and thereby alter bacterial fitness or virulence.

With greater research, lysogenic conversion could be used to weaken bacteria, providing the opportunity to "mute" the mechanisms of pathogenicity, thus rendering antibiotic resistant organisms harmless. This process can be stable for thousands of generations. Thus, lysogenic activated phages allow for bacteria to remain in the environment, preserving microbial balance. As we've demonstrated in the agricultural landscape and the microbial environment - nature favors heterogeneity. Lysogenic phages may provide a means to preserve that balance.

The lysogenic cycle propels phage research as a means of deprogramming and reprogramming antibiotic resistant pathogens rather than killing them off. In addition, phage-

[22]Harald Brüssow, Carlos Canchaya, Wolf-Dietrich Hardt. *"Phages and the Evolution of Bacterial Pathogens: from Genomic Rearrangements to Lysogenic Conversion"*

deprogrammed bacteria could potentially be used like a vaccine, helping the human body to develop defense mechanisms to organically fight new pathogens. This method will strengthen systematic defenses against future strains of antibiotic resistant organisms.

Some success using phages has been demonstrated by two-phase prospective intervention study was performed at a 945-bed public teaching hospital in eastern Taiwan. From March to December 2013, the researchers performed terminal cleaning using standard procedures plus an aerosol with active bacteriophage in the intensive care units to evaluate the impact on nosocomial incidence density, carbapenem-resistance rates and antimicrobial drug consumption amounts. The rates of new acquisitions of CRAB in the intensive care units decreased from 8.57 per 1000 patient-days in the pre-intervention period to 5.11 per 1000 patient-days in the intervention period ($p = 0.0029$). The mean percentage of resistant isolates CRAB decreased from 87.76% to 46.07% in the intensive care units ($p = 0.001$). All of the antimicrobials showed a significant reduction in consumption except imipenem. Ultimately, implementation of this dual pronged approach was successful in decreasing the rates of infection caused by CRAB across intensive care units in a large teaching hospital.[23]

2.4 Misnomers and Misidentification

The original dilemma still remains: if we can't comprehensively identify good bacteria, will we be able to implement phages, populate hospitals with good bacteria or recreate the microbial food chain? Technology enabling rapid and accurate identification has remained elusive until recently.

[23] Yu-Huai Ho et al. *"Application of Bacteriophage-containing Aerosol against Nosocomial Transmission of Carbapenem-Resistant Acinetobacter baumannii in an Intensive Care Unit"*

Microarrays may be the key to overcoming this information deficit. This technology is capable of quantitating hundreds or thousands of gene transcripts from a given cell or tissue sample simultaneously. A microarray contains thousands of DNA fragments or oligonucleotides of a known sequence arrayed in a known sequence of rows and columns on a chip. Recent developments in microarrays have increased speed and throughput. Microarrays enable a researcher to circumvent the difficulties of creating a culture. Important differences at hybridization signals observed in intergenic regions enable discrimination between different bacterial strains of a species. With the latest technological advances, one can envision array designs that will allow tiled representation of entire microbial genomes, discriminating strains almost down to single nucleotide level. One design in particular stands out, however.

Gary Andersen, Todd DeSantis, and their colleagues at Berkeley Lab have invented a fast DNA microarray called PhyloChip. This array probes samples for the 16S rRNA gene, which is involved in making proteins and is found in all bacteria and archaea. Analyzing samples from any source—such as air, water, soil, blood, or tissue—this microarray quickly and accurately identifies known and unknown organisms. In a recent test, the quality of the results from this microarray were demonstrated by cataloging the bacteria in air samples taken from two Texas cities. Over 1,800 types of bacteria were found in these samples.

PhyloChip has also already been used to study biological degradation of toxic chemicals, bioremediation of uranium, microbial composition of the atmosphere due to climate change, and the pathogenic colonization of lungs in intubated patients. NASA has employed the phylochip to study air quality in Jet airliners.[24] By harnessing air capture technology, hospitals can potentially

[24] *PhyloChip: DNA Microarray for Rapid Profiling of Microbial Populations IB-2229*

determine the biological load of a patient room, the pharmacy or even the operating room without ever having to grow a culture.

2.5 A New Toolkit

The hospital ecosystem is complex, containing a wide variety of microorganisms. Proper management of these microorganisms is critical to patient care. Proactive measures must be taken in order to combat the looming threat of antibiotic resistance. Thus, building effective environmental management practices requires numerous tactics. Synthesizing different fields and thought processes will be critical when building the hospital tool kit of the future. Doctor's nurses and healthcare workers will be challenged to examine the hospital ecosystem as they would a patient's symptoms.

Chapter 3: Recalculating Risk

Technological advances have made humankind more aware of hazards and dangers than ever before. The vast distribution of knowledge across the internet has opened our eyes to the many ways we can get injured, acquire a disease and even die. It thus follows that in order to survive - risk analysis has become an innate and unconscious component of human life.

We lack the time or capabilities to process the risk associated with each event we encounter. For example: most of us do not assess the possibility of a car accident, each time we get into a car. We do not analyze the weather, traffic for that day, other drivers on the road or thousands of other variables that may affect the outcome of driving. Instead, we utilize our past experiences as a benchmark for a quick assessment of current or future risk. Our shortcuts, rules of thumb, stereotypes and biases are generally known as "heuristics." These heuristics affect how we think about our choices, how we evaluate the probability of future events, how we consider costs, and how we make trade-offs. This mechanism generates close-to-optimal answers quickly, with limited cognitive capabilities.

3.1 Heuristics and Hospitals

Variations in minute details may significantly impact the outcome of heuristics. These variations cause us to go in search of advisors or confidantes. Outsourcing part of the decision-making process doesn't just occur when determining whether to drive on a rainy day. Risk analysts and consultants frequently evaluate important decisions on a large scale. They may specialize in a particular field, form of analysis or change that their client lacks. Outsourcing risk analysis is integral to receiving healthcare. Upon seeking the advice of healthcare practitioners, we are acknowledging that we need assistance calculating and understanding events beyond our life experiences. Health professionals work hard to ensure that the solutions they provide are

accurate and effective - their lives are dedicated to reducing the risk that comes with living. However, there is significant risk that healthcare professionals overlook in the treatment process - the risk of entry. Our assumption - built from years of experience - tells our heuristics that hospitals mitigate risk. But this is a miscalculation, based on an absence of data.

3.2 A New Risk Management Systems

The system for evaluating the risk associated with hospital operations typically revolve around the following areas of medical administration:

- Financing, insurance, and claims management
- Event and incident management
- Clinical research
- Psychological and human healthcare
- Emergency preparedness

Healthcare managers evaluate these internal departments as a means to reduce injury to patients, staff members, and visitors. Operations are strategically assessed in order to prevent incidents or minimize the damages following an event. In addition, healthcare practitioners perform a risk assessment on a patient-by-patient basis. This process consists of informal questions, medication reconciliation and formal health records that allow a practitioner to determine the best course of future actions. By gathering and interpreting this data, the practitioner may inform the patient on the predicted success of a lifestyle change, medication or surgical procedure. Ultimately, risk analysis comes in many forms and is a critical component of the healthcare continuum.

However, there is one aspect of patient health that is devoid of an intensive risk analysis - the hospital environment itself. Entering a hospital poses an uncalculated structural and environmental risk for vulnerable patients. The diverse microbiome exposes patients to a wide range of harmful bacteria and viruses. Although hospitals tout sterile practices, they

lack a quantitative analysis ensuring the efficacy of these practices. There is no doubt this oversight is costly - with over 100,000 lives lost to Hospital Acquired Infections alone. The danger lies in the unknown. Without pathogenic tracking data, it is impossible to treat this problem at its source. Thus, when a compromised and vulnerable patient enters the hospital environment, their risk is escalated.

The microbiome of a hospital poses a threat to patients and makes environmental management even more crucial to managing risk. If administrators, facility managers and healthcare practitioners continue to ignore the microbiome it can lead to disastrous patient outcomes. Administrators at the Seattle Children's Hospital failed to account for the risk associated with microbiome and experienced these consequences firsthand. Between 2001 and 2018, 14 patients developed aspergillus surgical site infections at the Seattle Children's Hospital Operating Rooms. Out of those 14, six patients died. [25]Upon investigation it was determined that mold-linked infections within the operating rooms led to six deaths previously thought to be isolated events. An investigation concluded that these deaths were attributable to " the air handling systems that serve our operating rooms," Dr. Jeff Sperring, the hospital's CEO, said in a statement. In order to rectify the disaster, "two custom-built air handlers will be installed and in-room HEPA air filtration systems will be employed in all operating rooms." Overlooked ventilation systems and lack of HEPA filter changes enabled Aspergillus, a dangerous fungus to grow and multiply - killing patients in its wake.

This case demonstrates the clear need for integration of the microbiome into the historical definition of healthcare - the classic "doctor - patient relationship". Although the refurbishment of the HEPA filtration system is critical to developing a comprehensive solution, it does not

[25]JEFFERY MARTIN, *SEATTLE CHILDREN'S HOSPITAL CLOSING 10 OPERATING ROOMS AFTER MOLD KILLS SIX*

address the root problem. Perhaps a faulty filter is installed - there is no way to determine if the mold is still present until someone dies. Seattle Children's Hospital, like every other hospital in the country, needs a new benchmarking system for the hospital microbiome must be created. By quantifying pathogens within segmented locations of the hospital, this analysis accounts for the unique microbiome within Pharmacy, ICU, NICU, ER. Real-time data will give practitioners a better understanding of how their actions affect the bio-load - quantifying particles and pathogens with each door opening in the Operating Room. The system will inform EVS workers on their efficacy and build insights into smarter cleaning techniques. But most importantly, it can be used as an early warning system - saving the lives of vulnerable patients. For the first time, administrators would have a real-time diagnosis of the environment. Corrective action will occur in real-time, not after lives are lost.

3.3 Shifting the Mental Model

Executing a new risk management system requires a transformation in the mental model hospitals operate upon. Mental models are important to developing new opportunities and recognizing innovation because they shape our perception of connections and simplify complex systems. Until now, mental models within healthcare revolved around the practitioners' ability to deliver a certain level of surgical performance, quality of care and patient outcomes. The mental model of healthcare practitioners will need to incorporate significant environmental consideration. No longer will the surgical tools count signal a completed surgery. The post-op checklist will begin, continue and end with constant environmental evaluation.

In order to achieve this medical staff will need to understand the hospital from an engineering and architectural perspective. To be clear, this is not a call for healthcare practitioners to become engineers and architects. Rather, it is a call to understand the mechanics

behind best practices so that they may experience continual improvement. For example, each time a door opens in the Operating Room, it causes the air exchanges to increase to maintain positive pressure. These door openings can have a negative effect on laminar flow, causing additional eddy currents that put the surgical site at greater risk to pathogenic exposure. Understanding these concepts and others like it attaches a significant "why" to a practice, creating better execution.

Although engineering is an integral component of hospital design – its methodology is not actively employed to maintain the environment. The boilers, generators and HEPA filters are all products of engineering - but they lack continued integration into the hospital mental model. Upon installation, they are maintained adequately but not applied to their fullest extent. For example, because HEPA filters are integral to airflow and particle reduction - they can also be used throughout the care continuum to secure and measure the biological load within an operating room. But few hospitals employ this practice. This could be equated to the wheel of a bike lacking a chain – technically the wheel is still functional. However, it loses a great deal of value without the whole system.

The culture of healthcare touts humanism as an important mental model for practicing healing – and it is. But when looking through a humanist lens we tend to forget that even within a humanist culture – a systematic approach can drive innovation. The mental model that drives laminar flow and many other hospital mechanics is an "input to output" methodology. This systemic approach to problem solving and creation enables a concrete – mathematical understanding of how the future product (the Operating Room bio-load) may react or perform in a variety of scenarios. Careful data gathering fuels future modifications and with each revision –

the product is optimized. This is not trial and error, but rather a careful refinement procedure entrenched in mathematical analysis. Thus by using environmentally-focused, data-driven insights and analytics, hospitals can implement practices that keep patients healthier. Data about the physical environment will fuel an improved continuum of care.

3.4 Key Players for Implementation

Shifting the mental model requires the active collaboration of different hospital operations. The first step to this is recognizing that hospital functions comprise many players: Environment Services, Plant Operations, Facilities Management, Infection Prevention and many others. Implementation of this new mental model requires hospitals to break down silos between each of these departments.

Environment Services, Plant Operations, Facilities Management, Infection Prevention are often unseen by patients but are the foundation - quite literally, the bedrock upon which hospitals are built. The absence of any one of these services could bring a hospital to its knees. Boilers, generators and cooling towers could easily wipe out a small city if improperly managed. They manage, insure and provide: temperature, humidity, medical gas, ventilation and electrical systems. Temperature and humidity help maintain patient stability. Medical gas provides life-support systems and surgical needs. Ventilation and HEPA filtration ensure clean, high quality air. The electrical systems provided by the generators enable doctors and nurses to deliver outcomes in life-threatening situations. For the sake of their patients - each of these must remain functional even in the most dire circumstances - withstanding a range of dangerous weather conditions and city grid outages. But these fields are too often called upon as reactive controls to emergency situations. Data from these departments must be brought under proactive assessment and used to preventatively manage patients spaces.

Implementation of the mental model will directly employ the vast data that Infection Control, Plant Operations and Facility Management has to offer. By examining the functionality of HEPA filtration systems, humidity and pathogenic instances in a singular format, hospitals will be able to shed light on patient outcomes. This input to output methodology will transform future risk calculations and create a platform for innovation and growth. Implementation of this new system will be explored in the Operating Room - where hospital acquired infections are the most deadly and debilitating.

Chapter 4: The Operating Room

At its core, the Operating Room is designed to function as a sterile environment. However, surgical site infection rates demonstrate that more stringent practices are necessary. Efficacy can be increased by removing data silos and implementing practices from industries such as chip manufacturing and pharmaceutical production. Industrial cleanroom best practices must be tailored to fit the unique nature of the Operating Room. With these new tools, hospital administrators will minimize and manage risk more effectively - enabling more patients to safely, healthily and happily return home to their families.

4.1 Introduction to the Operating Room Space

Developing a new model requires a deep understanding of the existing system within the operating room environment. Contrary to what the white-wash walls and standard equipment topography portray - each Operating Room has a unique fingerprint. This unique fingerprint is a consequence of minute architecture differences, site specific surgical procedures, clinical teams and fluctuating equipment placement. As procedures progress, surgical teams rotate and equipment exits causing the operating room's microbial landscape to shift with it. Numerous studies have demonstrated that the position of attending physicians, equipment and personal practices impact biological load, and thus surgical site infection rates. This begs the question, "What is the combination of components that will positively impact the operating room environment?" Quantifying the effects of these characteristics will streamline operating room functions and establish best practices.

The "landscape" or architectural structure of the operating room dictates how micro-organisms live and move within the space - much like an ecosystem. But unlike a natural ecosystem, these key players hold the blueprints to success:

The American Society of Healthcare Engineers (ASHE)
The American Institute of Architect's Guidelines for Health Care Facilities (AIA - AHA)
The Joint Commission (JC)
Facilities Guideline Institute (FGI)
National Fire Safety Standards

At the base level, the Operating Room environment is managed by Facilities, Plant Operations and Environment Services. However, its design is dictated and regulated by the Facilities Guideline Institute, American Institute of Architects and American Society of Healthcare Engineers. The literature and resources these organizations publish provide the baseline and building specifications for the operating room landscape. In turn, this baseline can be used to provide insight into optimizing the operating room ecosystem.

The Facility Guidelines Institute recommends a minimum of 400 sq. ft. for an inpatient Operating Room. A minimum of 600 sq. ft. is designated for specialized procedures and certain classifications. This relative standardization range is based on the need to accommodate large equipment, the movement of surgical staff during procedures and the maintenance of sterile space throughout the procedure. In addition, the size of an operating room impacts the sterility because it dictates the number of laminar diffusers, the calculated airflow velocity, and the calculated number of air exchanges. Each of these features affects the movement of pathogens within the ecosystem because they play an integral role in laminar flow and positive pressure. As discussed previously, maintaining laminar flow is critical to protecting the surgical site from contact with pathogens. As is, building an operating room to specifications is a complex process. Increasing the necessary problem solving, architects must work around ventilation and ductwork puzzles, aging building patterns and complex layouts to achieve their design goals.

Within the 600 sq. ft. lies one of the most important components of the OR - the sterile field. A sterile field is established through the installation of laminar diffusers containing high

efficiency particulate air (HEPA) filters. HEPA filters remove 99.99% of particles from the air that enters the room through the laminar diffusers. They serve to create a low particulate environment and push particles shedding from the surgical staff, to the floor. This is intended to reduce patient risk because particle counts can be directly correlated to biological load within the space. Continuous airflow keeps these particles below the operating room table. If a disruption in this airflow occurs, or large pieces of equipment are present in the room, eddy currents form. This is extremely problematic for maintaining the sterile field as these eddy currents can cause particles to rise towards the surgical site. This risk can be reduced through high and low placement of return ventilation, and the elimination of corners within the operating room. Beveled or rounded walls can help direct airflow towards vents and minimize eddy currents.

According to FGI, the air within the sterile field must be exchanged at a minimum rate of 20 exchanges per hour. In addition to this, 4 outdoor air exchanges are required. This keeps fresh air coming into the hospital environment. Air exchange rates are achieved by pushing the air through a HEPA filtration system and laminar diffuser grid installed in the ceiling. There are many different potential designs for these grids and installation is at the architects' and hospital's discretion. An operating room may have a system ranging from a fully covered rectangular diffuser to a system that merely forms a rectangular outline around the bed. This will cause discrepancies in efficacy. Not all diffuser systems are created equal in their ability to protect the surgical site. The only other requirement comes from ASHE Standard 170. It requires that air must be exchanged at the ceiling and exhausted at low wall grilles. Standard 170 dictates that a minimum of two low grilles, 8 inches above the floor are necessary, spaced at opposite corners or as far apart as possible.

As specified by FGI, the operating room must remain between 30-60% humidity and 68-75 degrees Fahrenheit. The designation of a minimum humidity level at 30% Relative Humidity is a hold-over from the days of flammable anesthe-sia. All too often, administrators investigating surgical site infection rates, evaluate humidity as the most significant indicator. However, the ideal humidity for common operating room pathogens ranges from 15% to 85%RH. With such a dispersed group, it is nearly impossible to declare a 30-60 % RH range with authority unless it is to ensure patient and physician comfort. Further research into relative humidity demonstrates its minimal role in surgical site infections and biological load within the Operating Room. Unless humidity is consistently hitting 90% RH and above, it is unlikely pathogens are actively growing within the space. This lack of growth can be attributed to the terminal cleans that remove potential food sources. Nonetheless, this demonstrates an interesting problem - attributing surgical site infections to a cause without significant data.

Physician practice is also a critical component of the operating room and is directly affected by the size of the sterile field and equipment placement. As the ambulatory nurse moves around the sterile field while the operating room surgeons work within it, both parties' movement is limited by the size of the sterile field. In addition it is recommended that clinicians enter and exit the field facing it, and turning one's back to the field is highly discouraged within the operating room space. Any object or body part that rests below the surgical table is considered to no longer be sterile. But these practices can even be improved, leveraged with better data insights. For example, particulate mapping can show surgical staff the best point at which to enter the sterile field based upon laminar flow pathways in the room. This will improve the cleanliness of the entering staff members and reduce patient risk.

Frankly, it is no longer acceptable to tout the three foot difference between the operating room table and the floor as a mode of patient protection. It is time to understand how each of the operating room components discussed affect pathogens and the protection of the surgical site. Furthermore, there are industries and fields far more successful at installing sterile environments with practices that can and should be applied to the operating room.

4.2 Optimization According to Clean Rooms

In order to create a more sterile space, hospitals can learn from other industries. Microchip Manufacturing is one of the most sterile industries in the world - because it has to be. A single dust particle from a strand of hair is all it takes to ruin a CPU that might sell for $500, so companies are eager to minimize how often that happens. [26]

The process of making chips is called fabrication. Inside Intel's ultra-clean fabrication rooms, the world's most complex, tiniest machines — processors and other silicon chips — are built in a special area called a cleanroom. Because particles of dust can ruin the complex circuitry on a chip, cleanroom air must be ultraclean. Purified air is constantly recirculated, entering through the ceiling and exiting through floor tiles. Technicians put on a special suit, commonly called a bunny suit, before they enter a cleanroom. This helps keep contaminants such as lint and hair off the wafers. Although this process also occurs in the operating room, fabrication bunny suits have some differences. Fabrication bunny suits cover the entire body from feet to face and are worn constantly - preventing the shedding of squames that is often seen in the operating room.

In a cleanroom, a cubic foot of air contains less than one particle measuring about 0.5 micron (millionth of a meter) across. That's thousands of times cleaner than a hospital operating

[26] **A Chip Is Born: Inside a State-of-the-Art Clean Room, John Snyder**

room. [27] A number of techniques are used to create this ultraclean environment. Similar to Operating Rooms, Cleanrooms use High Efficiency Particulate Air (HEPA) filtered air. HEPA filtration has an efficiency of 99.97% down to 0.3 microns. The HEPA filters for stringent cleanrooms such as those in chip fabrication are normally located at the terminal end and in most cases provide 100% ceiling coverage. "Dirty air" is funneled through grates on the floor. This creates a laminar flow in which all particles are pushed downwards. This is not the case in hospital operating rooms. Operating rooms lack full ceiling filtration, creating eddy currents that bounce particles off of the walls. This is highly problematic in containing particles entering and exiting the space as operating room doors open frequently due to less stringent entry and exit codes.

In order to ensure consistently low particle counts and monitor for aberrations, cleanrooms are tested via particle counters. They consist of specialized optics, lasers, carefully aligned sampling regions, and printed circuit boards (PCBs). Environmental stressors like dirt, heat/cold extremes, electromagnetic interference (EMI), and vibration affect the extremely sensitive measurement. Particle counters are high-sensitivity, high-performance electronics devices that can be employed for data interpretation, trend tracking, and statistically valid sampling.

Cleanroom Particle counters are used to determine the cleanliness of the room which in effect contributes to the control of airflow. Some cleanroom controls are driven by real time cleanliness monitoring depending on the criticality of the process of which the cleanroom encompasses. Particle counters are used to monitor the many sizes of particles of concern for a given cleanroom's contamination control problem. The number and placement of counters will

[27] *Chip Manufacturing in Semiconductor Cleanrooms*

need to be determined through interaction with process engineers and may involve some experimentation. An output signal from the particle counters can directly control recirculation fan speed. Most of today's high-tech processes require an absence of particulates. For example, pharmaceutical companies monitor 0.5 μm particles to determine process cleanliness, and 5 μm particles to determine product sterility. Conversely, semiconductor manufacturing tends to focus on particles from 0.3 μm down to 0.05 μm.[28] There are several different types of particle counters employed to secure these processes:

Remote Particle Counters:

Small particle counters that are used to monitor a fixed location typically inside a cleanroom or mini-environment to continuously monitor particle levels. These smaller counters typically do not have a local display and are connected to a network of other particle counters and other types of sensors to monitor the overall cleanroom performance. The computer based network is interconnected to control environmental conditions, airflow etc.

Manifold Particle Counters:

These are a modified aerosol portable particle counter that has been attached to a sequencing sampling system. The sequencing sampling system allows for one particle counter to sample multiple locations, via a series of tubes drawing air from up to 32 locations inside a cleanroom. Typically less expensive than utilizing remote particle counters, each tube is monitored in sequence. This allows for the system to account for fluctuations in a variety of areas, narrowing down any potential problems with the cleanroom mechanics.

Hand-held Particle Counter:

[28] *Clean Room Particle Counters by Cleanroom Company Directory*

A hand-held particle counter is a small, self-contained device that is easily transported and used, and designed for use with Indoor Air Quality (IAQ) investigations. Though lower flow rates of 0.1 ft^3/min (0.2 m^3/h) than larger portables with 1 ft^3/m (2 m^3/h), hand-helds are useful for most of the same applications. However, longer sample times may be required when performing cleanroom certification and testing. Hand-held counters are not recommended for Chip Fabrication Cleanrooms due the size of the environment. Most hand-held particle counters have direct mount isokinetic sampling probes. It is recommended that the length of the tubing not exceed 6 ft. (1.8 m), due to loss of larger particles in the sample tubing.

The Federal Industry Standard 209 and the International Organization for Standardization (ISO) create standards for particle concentrations in clean processes. ISO 14644-1 establishes standard classes of air cleanliness for cleanrooms and clean zones, based on specified concentrations of airborne particulates. Quantification of particles is critical to ensure proper functioning of the laminar diffuser systems and containment. The table below lists the specific allowable particle limits per Standard 209 and the ISO Class.

The classification table dictates that a Class 100 cleanroom, for example, would not contain more than 100 particles bigger than *0.5 micron in a cubic foot of air*. A Class 10,000 - particle count not exceeding a total of 10,000 particles per cubic foot of a size 0.5 microns and larger or 70 particles per cubic foot of a size 5.0 microns and larger. Typically, Class 1 & 10 are designated production laboratories for electronic integrated circuits. Class 100 clean rooms are designated for photo labs and medical implant production. Class 10,000 clean rooms are

designated for production locales for TV tubes, hospital operating theaters. Class 100,000 are designated for the production of ball bearings. [29]

Class	0.1 µm	0.2 µm	0.3 µm	0.5 µm	5 µm
1	35	7	3	1	
10	350	75	30	10	
100	3500	750	300	100	
1,000				1,000	7
10,000				10,000	70
100,000				100,000	700

Class	0.1 µm	0.2 µm	0.3 µm	0.5 µm	1 µm	5 µm
ISO 1	10	2				
ISO 2	100	24	10	4		
ISO 3	1000	237	102	35	8	
ISO 4	10000	2370	1020	352	83	
ISO 5	100000	23700	10200	3520	832	29
ISO 6	1000000	237000	102000	35200	8320	293
ISO 7				352000	83200	2930
ISO 8				3520000	832000	29300
ISO 9				35200000	8320000	293000

Upon quantifying the particles, pharmaceutical and biotech cleanrooms identify the particles present. In an earlier chapter, we touched on a microchip technology as potential means for particle identification. Another solution, currently employed in industrial cleanrooms is the Orum International and Hardy Diagnostics MULTIFLEX 1+2 active impact microbial air sampler. This air sampler further ensures the quality of air as the presence of bacteria or spores hanging in the air can have a negative effect of products.

The techniques and equipment utilized by chip manufacturers and pharmaceutical companies present a massive opportunity for innovation within the operating room. These resources will build the next generation of safer surgical practices. Optimizing laminar flow within the operating room will reduce particle entry and exit as physicians move throughout the space. Quantifying and identifying particle counts will create intelligent data sets to guide best practices. Smart technology can be implemented to tell doctors when particle counts and types

[29] *HVAC Design for Cleanroom Facilities, A. Bhatia*

become too high or too dangerous. Tailoring cleanroom infrastructure will enable real-time assessment of patient risk.

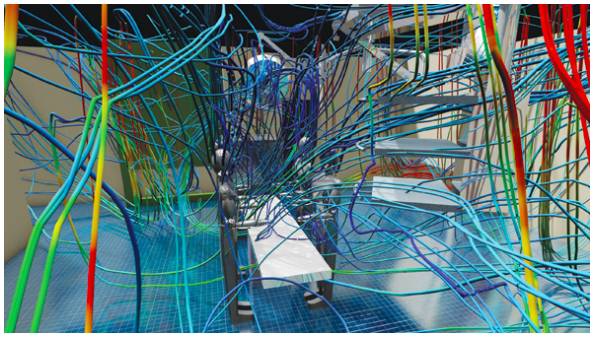
4.3 Transferring and Tailoring Cleanroom Methodology

In theory, Operating Room and Cleanrooms are synonymous. Each impose sterility regulations on highly valuable materials - the human body and the microchip. However, when it comes to quantification and execution of sterility standards, cleanrooms are far more successful. More regulations and preventative measures exist to control the production environment for a $500 piece of metal and plastic, than the environment in which human life is at stake. In that context, our standards are appalling.

One significant barrier to optimizing the Operating Room is human touch. While AI technology and robots can be utilized in the chip fab production line, human surgeons are still integral to the health continuum. Significant particle quantities will be present where human doctors are present. As a doctor or supporting staff member enters the operating room, particles will trail in his or her wake. If a member of the team forgets to change their cap or wears the same shoes outside the operating room environment, particles will be introduced. Direct transference of cleanroom technology will not produce the same results in the operating room. Eliminating particles from the Operating Room completely would require the removal of the human component of healthcare. Therefore, it is necessary to tailor cleanroom techniques to include human intervention, reducing the risk that human doctors create.

The first step towards optimizing the Operating Room is through laminar flow. The full ceiling diffusers implemented by cleanrooms create air pathways that effectively usher particles out of the environment. As demonstrated by the images on the right, laminar diffusers can play

an integral role in airflow and particulate control within the operating room.[30] Unfortunately, refurbishing Operating Rooms with full ceiling diffuser systems comparable to industrial cleanrooms is an unrealistic recommendation due to logistical, maintenance and financial concerns. Full ceiling diffusers would require rerouting of extensive ductwork in order to maintain a constant air supply. In addition, the HEPA filters necessary have a relatively short and expensive shelf life. Construction costs for a cleanroom facility, along with its maintenance and certification, are extremely high. Average construction costs for a cleanroom range from approximately $260/sq. ft. for Class 100,000 to about $525/sq. ft. for Class 100. In addition to this sizable initial investment, normal maintenance costs are about $75/sq. ft. The sheer amount of energy it takes to maintain 50 air exchanges per hour is massive. In addition, the revenue lost during the redesign of these facilities would need to be accounted for. A realistic solution must parse and apply cleanroom techniques purposefully.



Instead a partial laminar diffuser system can be installed in the Operating Room. While many operating rooms contain a diffuser system, the set up should be optimized further. Research executed by Memarzadeh and Manning demonstrates that certain diffuser systems are more effective at protecting the surgical site from particle encounters. In the study, *Effect of Operation Room Geometry and Ventilation System Parameter Variations on the Protection of*

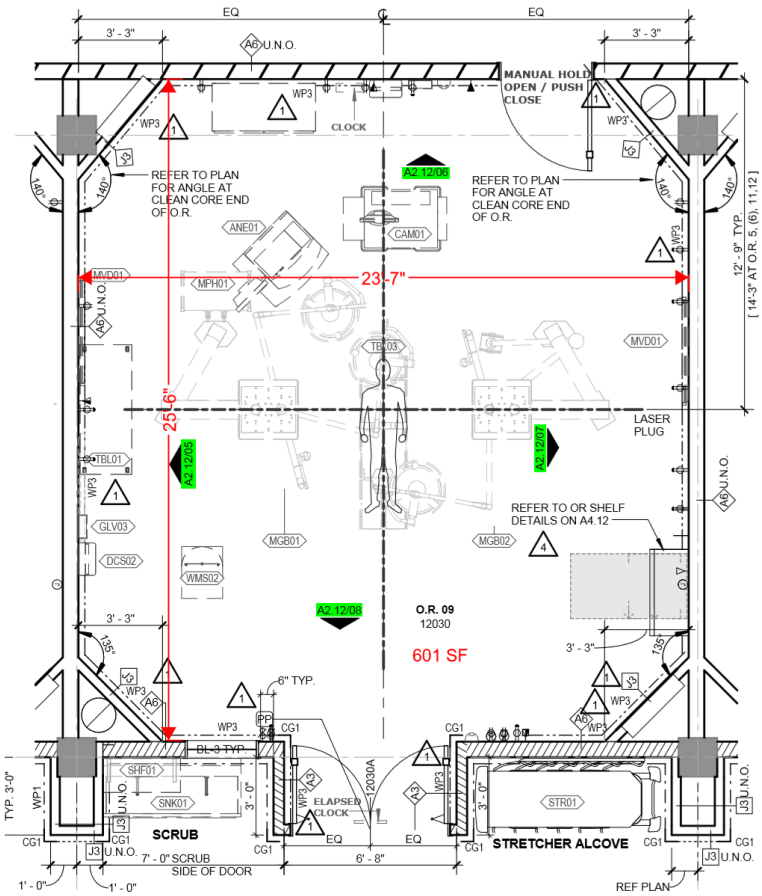
[30] Computational fluid-dynamics (CFD) keeps operating rooms clean, Stephen Mraz

the Surgical Site, airflow modeling and particle tracking methodologies were used to consider the effect of geometry changes—in particular, ceiling height variations—in an operating room (OR). In a second study, *Effect of Operation Room Geometry and Ventilation System Parameter Variations on the Protection of the Surgical Site,* Memarzadeh and Manning mapped the operating room environment to explore how particulate movement and operating room attendants affect the percentage of particle counts hitting the surgical site. Of a variety of ventilation types, systems with four, mixed exhaust returns protect the surgical site most effectively. Though two low exhaust grilles are dictated within FGI, cases with the same air exchanges show marked differences in terms of the percentage of particles removed via ventilation. While this is critical information, it requires greater assessment on a broad scale during operations. Up until this point, such testing has been impossible due to restrictions of operating room access and the difficulty of tracking particles. However, pulling from other industries, hospitals can begin the next step toward validating these models. It will require monitoring the number of particles present, in real time, over the course of hundreds of procedures.

The next step towards optimization will utilize a technique found in chip fabrication and pharmaceuticals - particle counts monitors. Particle count monitors come in various shapes and sizes, enabling customization per operating room. The monitors do not simply track the numbers of particles but also the size of those present. Pairing particle counts with microbial monitors will give administrators a deeper understanding of their operating room environment. This information can then be applied to a mapping system created from the OR floor plan shown on the right. This mapping system will be able to identify high particulate areas in real-time, as doctors, patients and supporting staff move through the space. If particle counts are above a

particular level it will alert the physician on duty, allowing them to increase airflow, change the location of a particular surgical cart or monitor door openings more closely. The mapping system will enable administrators and doctors to understand how operating room practices affect outcomes.

This system will ensure administrators will have a wealth of significant data when a surgical site infection occurs. For example, if a patient receives MRSA and records count said particulates in the operating room environment, administrators can begin to evaluate clinical practices contributing to the transmission. The MRSA infection would be able to be tied to a particular door opening or the blockage of a vent. Particle counts and microbial monitors can also be used to hypothesize the method of transmission. For example, it is more likely that SSIs in superficial wounds are created from the patient's own squames (skin cells) that have contaminated the wound. This contrasts deep incisions and organ space infections that are more likely to be caused by airborne particles contaminating the wound. High Deep Incisional or Organ Space SSIs and low particle counts will correlate to poor aseptic or surgical practice. High Superficial Incisional SSIs and high particle counts will correlate to poor environmental management. However, if



02 OR 9 / TYPICAL OR ENLARGED FLOOR PLAN
1/4" = 1'-0"

the system does not identify any particles of that size or nature, then administrators would be able to determine that the infection occurred in another area of the hospital. Thus administrators are able to hone in on the department or personnel needing retraining or tightened practices. Particulate counting may also point to evidence that such an infection occurred outside the hospital.

Incorporating these quantification methods will give administrators and doctors clear evidence as to why SSI rates are increasing or decreasing. Particle counts and microbial monitors act as another measure to managing patient care, giving administrators and physicians a clearer understanding of how operating room practices are affecting surgical outcomes. In addition, rates can significantly impact revenue analysis. This process turns a reactive punishment into a proactive warning system. Over time, it will enable physicians to clarify operating room best practices in concert with engineering systems. It is important to keep in mind the big picture - surgical site infections are a matter of life and death.

4.4 Future Applications

Trends in the healthcare system show a shift towards procedures outside of the hospital environment, reaping effects yet to be seen. Ambulatory surgical systems are increasing in popularity. For at-risk patients, having a procedure in an ambulatory surgical center may reduce their risk of a surgical site infection. Removing that patient from the highly-traversed hospital environment decreases bacterial exposure per patient. The human body loses 30,000 squames per hour, each containing 100 bacteria. As you might imagine, this adds up quite rapidly in high capacity Operating Rooms. A surgical center with a smaller patient capacity, will limit the number of bacteria entering and exiting.

However, ambulatory surgical centers may increase patient risk due to a lack of structural support. Small surgical centers may lack environment services, infection prevention staff and critical architectural components that ensure the sterile operating room environment. It is important to note that the risk for ambulatory surgical centers is an internal one. Decreased traffic decreases potential bacterial exposure from other sources. However, it does not decrease the risk the patient poses to himself. The patient can still receive an infection from his own squames, shed near the surgical site during the procedure. As the squames are dislodged from the skin, the lack of a laminar diffuser system increases the likelihood that a patient may "self-infect".

Trends in surgical care have created ambiguity as to best practices for patients. It is time to begin quantifying these practices in order to better protect patients. In order to do this, hospitals will need to implement new testing procedures in their operating rooms.

Chapter 5: Validating and Testing

Validating and testing stipulates the need for controlled conditions, but due to procedure variability the operating room often lacks this characteristic. In order to fix this, numerous trials to baseline the numbers to pathogenic size, distribution and severity will need to be run. This will help create a new system for determining operating ability. This system will be an expansion of current measures. The temperature, humidity and pressure gauges will ensure a foundational understanding of the environment. A particle counter mounted to the wall will show pathogen distribution throughout the room. In addition, regular microarraying will be used to identify the type of pathogens present.

5.1. Design of OR 28

Due to COVID-19, the study designed below was unable to reach the implementation and testing stage. The study would have been carried out in OR 28 of the Orthopedic Department of Seton Medical Center in Austin, Texas. OR 28 was opened in 2005. The operating room is equipped with a sterile field, created by a ceiling diffuser system and integrated with high-efficiency particulate (HEPA) filters. The air to OR 28 is supplied through fourteen diffusers, 24”x48”. The diffusers have a 8”neck and pump a total of 2,240 CFM. OR 28 also features two sidewall grille 13”x30” processing return air at 1,045 CFM in opposite corners of the room. According to research by Memarzadeh and Manning, Seton Operating Room 28, matches the design of a large single diffuser with two low exhaust grills.

Unlike some of the new operating rooms at Seton Medical Center, this OR does not contain schlamphered walls. This means that the room contains corners. It is important to note that not all of the operating rooms at Seton contain corners. In the more recently constructed operating rooms, the corners have been schlamphered or beveled in order to reduce the

likelihood of equipment placement or vent blockage. The room has two entry points via the sterile core and the (2.0 m × 1.5 m) opening to the main corridor. Air temperature and humidity were controlled using conventional HVAC methods at set points at approximate ranges of 50-65 degrees Fahrenheit and 35% ± 7% relative humidity, respectively. This operating room would have been studied over a 3 month period in order to assess its baseline particle count and surgical site infection occurrences.

5.2 Instrumentation

Particulate matter (PM) concentration and size distribution were measured using factory-calibrated stationary particle analyzer GrayWolf® Model PC - 4000 Series, these readings were validated using a factory calibrated hand-held particle analyzer. Before sampling, each particle counter was calibrated using a zero-check filter. The zero check filter purges the device of particles during a 5-min sampling time. After this sampling time, the particle count read out at zero. The particle analyzer sampled continuously at a rate of 0.283 □^{3}/min (accuracy ± 5%) and logged data at 10-s intervals to obtain sample volumes of 0.00472 m3 (28.3 L) of air per sample. The particles were recorded in the following sizes: 0.3, 0.5, 1.0, 3.0, 5.0 and 10.0 μm.

5.3 Experimental Set-Up and Procedure

The particle counters were housed within the return vents in order to examine the particulate flow. Their location was approximately 1 foot above the floor and approximately 8 feet from the porcine tissue under the surgical lights. Attached to a power source and connected to Wi-Fi, a continuous run was held for data mapping. The ventilation system was turned on approximately 30 min prior to the first surgery of the day and left to continuously work throughout the course of the day. A door opening counter was used to track entry and exits throughout the course of the day. Occupancy rates were recorded in time with procedure length.

5.4 Results - Or Lack Thereof

Due to the COVID-19 pandemic, data collection did not occur. All non-essential employees were barred from the hospital and the particle monitors were promptly removed from Operating Room 28. Instead, this section will address further preliminary data from the previous summer and the expected outcome of the experimental design.

It is important to note that preliminary data was collected over the course of the summer of 2019. The preliminary data acquired provided the proof of concept for existing eddy currents within the Operating Room - which signal a breakdown of laminar flow. The data also demonstrated a correlation between surgical equipment placement, door openings and high particulate spaces. However, these correlations lack rigor and will not be presented. The data itself lacks rigor due to the use of hand-held particle counters and variances among testing occurrences. Hand-held particle counters do not perform within the range of accuracy necessary to measure a cleanroom environment. By nature, hand-held particle counters require a human element - which made it impossible to test particle fluctuations during operating room procedures. The experimental design reflects these necessary validation changes by using a stationary, 24/7 particle monitor housed within the return vent.

Ideally, particle counts would have been collected over the course of three months to establish a baseline for Operating Room 28. This baseline would have been applied to a mapping system that enables the analyst to pinpoint comparatively high particulate areas. Mapping also enables the analyst to assess the efficacy of the current laminar flow system, without needing to execute a smoke test. The mapping system would have been matched to changes and particulates based on door openings. An evaluation of surgical site infection rates over the prior time period in order to evaluate any patterns, would have also been executed.

The 24/7 monitoring provides administrators with a critical understanding as to how scaling back air exchanges during the evening affects the operating room environment. The output of this analysis may be as simple as "During the course of the day, the mean particle count was found to be X. Upon the scaling back of the ORs in the evening, the particle count was found to be X. A higher particulate count during evening hours suggests that the energy saving scale back may be putting patients at risk. It is possible that the scale-back may continue - but an additional purge of the Operating Rooms must occur with adequate time before patient entry. Based on experimental evaluations, adequate time has been determined to be X minutes." This analysis would validate the necessary safety measures to continue cost-effective practices.

5.5 Future Variations of this Experiment

Future variations of this experiment will need to be performed in order to confirm that laminar flow fluctuates with equipment movement and personal practice. Particle counters would again be used to map fluctuations. This version of the experiment will require greater collaboration with the attending surgical staff in order to monitor equipment movement. Staff will place surgical instrument tables in specific locations and will enter the field according to the particulate mapping system. Door openings will be barred entirely during the procedure to further explore how laminar flow is preserved.

As the experiments continue, the operating rooms in Seton will be divided into an experimental group and a control group. Operating rooms are often high-turnover. It would be nearly impossible to restrict an operating room to a single type of procedure or surgical team without significant revenue loss. Therefore, when segmenting the experimental group and control group, careful attention must be paid to the different types of surgeries and teams working in each space. The segmented group must be balanced in order to provide significant

data insight across the entire operating suite. 24/7 particle counts will allow analysts to pick which surgical procedures to study, while honing in on team practices that may have caused comparative fluctuations.

This will require direct collaboration with surgical teams to properly segment the data collected and account for variances. Over the course of several months, infections will be tracked and compared to particle count maps. Ideally, the particulate maps will reveal the differences in biological load per operating room and surgical team. Practices surrounding the surgical teams will be examined for discontinuities affecting the environment. This may look like placing surgical carts in the direct pathway of a vent. Then, changes will be made to the operating room equipment set-up to eliminate blockage of the laminar flow according to high-risk areas. These changes will then be studied over the subsequent months to further explore how the particle counts shift and establish new baselines. Teams will be provided data on their door openings and particulate counts in later variations of the experiment in order to shift personal practices to reduce the movement of biological load.

Ultimately, this is a very broad look at a multi-experiment process. The entirety of this thesis could be dedicated to each experimental variation. As data is collected and analyzed, new factors will be uncovered. Therefore, future experimental designs must be fluid, agile and constantly updated in order to define the best operating room mechanisms and practices for patient safety.

5.6 A Final Caveat

The human component of health ensures that these experiments cannot control for every significant variable. By implementing in real-time, results are subjected to complicating factors. However, it is crucial that these experiments occur during actual procedures and with normally-

functioning surgical teams. This design provides the opportunity to reveal the true state of the operating room environment. If a build-out or computer rendering was employed to minimize variation, results would only reveal broad trends in operating room practices. Each operating room creates a unique landscape and therefore must be treated and tested as such. Comparative analysis and large samples, will assist in explaining anomalies or flaws. In order to build a system that can predict and react to the complexity within the operating room environment, we must expose the experimental design to an imperfect control.

With a better understanding of the operating room - surgical teams can minimize the likelihood that the infection occurs from the hospital environment itself. This design offers a new perspective for identifying what we can and cannot control within the operating room. When a trauma patient enters the operating room, it is highly likely that the skin has been broken. Due to the nature of the accident - dirt, bacteria and other contaminants are present within the wound before the patient even enters the operating room. Neither the proposed experiments, nor their product can prevent this. However, the system dictated by Operating Room Optimization provides the necessary data and insight to make more informed choices about patient care and protects the variables that hospitals can control.

Conclusion

There is no silver bullet. The complexity of the human condition creates a constant state of flux that healthcare organizations must adapt to. The entry of new pathogens, rising numbers of vulnerable populations, increase in antibiotic resistance and future trends in surgical procedures necessitate a new mental model. This mental model must focus on quantifying, analyzing and eliminating the environmental transmission of pathogens. In order to achieve success, hospitals will need to examine, tailor and implement cross-industry "best practices". Optimizing the Operating Room based on cleanroom techniques found in chip fabrication and pharmaceutical manufacturing represents the first step towards building a comprehensive system equipped to preserve and maximize the healing process.

Furthermore, the emergence of COVID-19 and its lack of immediately identifiable symptoms poignantly reinforces the need to intimately understand the movement and transmission of pathogens. There is no doubt that the current pandemic will permanently change the healthcare continuum. Building a new mental model will assist hospitals in leveraging cross-industry tools to proactively protect patients and their loved ones as further challenges present themselves.

Biography

Madison Cleff is a student-athlete at the University of Texas at Austin. She has dedicated her academic career to exploring the intersection of science, the human condition and the surrounding infrastructure. She intends to continue her interdisciplinary interests with the consulting firm, Oliver Wyman, upon graduation.

Outside of the classroom, she competes for the Division I University of Texas Women's Tennis team and holds two Big 12 Championship Titles. The eldest of four, Madison enjoys weekly Sunday night dinners with her brother, Ben, and sister, Reilly, who also attend UT. Her parents, David and Lisa, and youngest sister, Ella, are also huge Texas Longhorn fans! On the weekends you can find her running Lady Bird Lake, hiking with friends, trying out funky restaurants and singing all the wrong lyrics to Spotify's Top Hits.

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